Transactive Control & Coordination: A Double-Auction Based Approach to Distributed Control and Decision-making

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Control of Complex Systems Initiative: From Big Data to Big Controls

**CCSI**: A five year, multi-million dollar internal research investment to build and demonstrate development and delivery of best of class solutions for problems in the control of complex systems.

**Challenges for Big Controls:**
- Large numbers of sensing and/or control end points
- Multiple scales of operation usually with multiple time scales
- Node heterogeneity
- Pervasive computing/autonomous nodes

**Control solutions will be:**
*Scalable, deployable, robust, resilient, and adoptable.*
The challenges facing the grid are significant and in tension with each other

- Maintain and increase reliability
- Integrate renewables & low-carbon sources
- Potential electrification of vehicle transportation (& other end uses as electricity becomes the preferred “fuel”)
- Increase asset utilization, reduce capacity for peak loads and ramps
- *While keeping costs & revenues as low as possible*

Smart grid is the most promising approach to addressing these challenges simultaneously

- Much of smart grid’s promise lies in distributed assets: Demand response, distributed storage & generation, electric vehicles, smart inverters
Designing a novel control architecture for the power grid needs a significant number of considerations, e.g.:

- Laws of electro-physics must be observed
- Current/future stakeholder boundaries must be respected
- Architecture must be deployable in a modular, incremental fashion
- For reasons of robustness, resilience & flexibility, the control architecture must be layered
- Considering the huge number of assets, lowest layer must be a distributed control architecture

**Transactive Controls** is a very promising approach for such a distributed control architecture
Transactive Controls / Transactive Energy

Refers to *techniques for managing the generation, consumption or flow of electricity* within a power system, *using economic or market-based constructs*, while *respecting grid reliability constraints*.

The term “*transactive*” comes from considering that *decisions are made based on a value*. These decisions may be analogous to, or literally, economic transactions.

What Problems or Issues is Transactive Control and Coordination, TC2, Designed to Address?
## Principal Challenges Addressed by TC2

<table>
<thead>
<tr>
<th>Principal Challenge</th>
<th>Approach</th>
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<tbody>
<tr>
<td>Centralized optimization is unworkable</td>
<td>Distributed approach with self-organizing, self-optimizing properties of market-like constructs</td>
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<tr>
<td>for such large numbers of controllable assets, e.g. ~10^9 for full demand response participation</td>
<td></td>
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<tr>
<td>Interoperability</td>
<td>Simple information protocol, common between all nodes at all levels of system: quantity, price or value, &amp; time</td>
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<tr>
<td>Privacy &amp; security</td>
<td>Minimizes risks &amp; sensitivities by limiting content of data exchange to simple transactions</td>
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<td>due to sensitivity of the data required by centralized techniques</td>
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<tr>
<td>Scalability</td>
<td>Self-similar at all scales in the grid</td>
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<tr>
<td>Common paradigm for control &amp; communication among nodes of all types</td>
<td></td>
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<td>Ratio of parent to child nodes limited to ~10^3</td>
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### Principal Challenges Addressed by TC2 (cont.)

<table>
<thead>
<tr>
<th>Principal Challenge</th>
<th>Approach</th>
</tr>
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<tbody>
<tr>
<td>🔄 Level playing field for all assets of all types:</td>
<td>✅ Market-like construct provides equal opportunity for all assets</td>
</tr>
<tr>
<td>- <em>existing infrastructure &amp; new distributed assets</em></td>
<td>- Selects lowest cost, most willing assets to “get the job done”</td>
</tr>
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<td>🔄 Maintain customer autonomy</td>
<td>✅ Incentive-based construct maintains free will</td>
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<tr>
<td>- “Act locally but think globally …”</td>
<td>- <em>customers &amp; 3rd-parties fully control their assets yet collaborate (and get paid for it)</em></td>
</tr>
<tr>
<td>🔄 Achieving multiple objectives with assets essential for them to be cost effective</td>
<td>✅ Allows (but does not require) distribution utility to act as natural aggregator</td>
</tr>
<tr>
<td>- <em>address local constraints while representing the resource to the bulk grid</em></td>
<td></td>
</tr>
<tr>
<td>🔄 Stability &amp; controllability</td>
<td>✅ Feedback provides predictable, smooth, stable response from distributed assets</td>
</tr>
<tr>
<td></td>
<td>✅ Creates what is effectively closed loop control needed by grid operators</td>
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PNNL Transactive Energy Approach: *Transactive Control & Coordination (TC2)*
Precise, stable control of congested grid nodes derived from customer price-responsive bidding algorithm interacting with price discovery mechanism (e.g., a market)

Transactive Cooling Thermostat

More Comfort → More Savings

$/kWh

Price

Bid

Precise, stable control of congested grid nodes derived from customer price-responsive bidding algorithm interacting with price discovery mechanism (e.g., a market)

Real-time Market Clears Customer Bids

Price ($/MWh)

Load (MW)

$P_{clear}$

$P_{whole-sale}$

$Q_{clear}$

Demand Curve (customer bids)

Node Supply Curve

Rated Node Capacity

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Hierarchical Network of Transactive Nodes Parallels the Grid Infrastructure

**Node:** point in the grid where flow of power needs to be managed

**Node Functionality:**
- “Contract” for power it needs from the nodes supplying it
- “Offer” power to the nodes it supplies
- Resolve price (or cost) & quantity through a price discovery process
  - market clearing, for example
- Implement internal price-responsive controls
Properties of Transactive Nodes

- **Use** local conditions & global information to make control decisions for its own operation.

- Indicate their response to the network node(s) serving them:
  - to an *incentive signal* from the node(s) serving them.
  - as a *feedback signal* forecasting their projected net flow of electricity (production, delivery, or consumption).

- Setting incentive signal for nodes serves to obtain precise response from them, based on their feedback signals.

- Responsiveness is voluntary (set by the node owner).

- Response is typically automated (and reflected in the feedback signal).
Long-term objective for TC2 is to simultaneously achieve combined benefits

- Reduce peak loads (minimize new capacity, maximize asset utilization) – generation, transmission, & distribution
- Minimize wholesale prices/production costs
- Reduce transmission congestion costs
- Provide stabilizing services on dynamically-constrained transmission lines to free up capacity for renewables
- Provide ancillary services, ramping, & balancing (especially in light of renewables)
- Managing distribution voltages in light of rapid fluctuations in rooftop solar PV system output
Transactive Cooling Thermostat Generates Demand Bid based on Customer Settings

- User’s comfort/savings setting implies limits around normal setpoint ($T_{desired}$), temp. elasticity ($k$)
- Current temperature used to generate bid price at which AC will “run”
- AMI history can be used to estimate bid quantity (AC power)
- Market sorts bids & quantities into demand curve, clears market returns clearing price
- Thermostat adjusts setpoint to reflect clearing price & temperature elasticity

Translates to: $k$, $T_{max}$, $T_{min}$
RTP Double Auction Market – **Uncongested**

- **Market clears every** $T_S = 5\text{min}$ (to ~match AC load cycle)
- **When uncongested:**
  - Quantity ($Q_{\text{clear}}$) varies with demand curve
  - Price ($P_{\text{clear}}$) is constant, equal to Base RTP

**Demand Curve:** sorted $(P, Q)$ bids from trans-active customers

Market clears at intersection of supply & demand curves

**Retail RTP** based on wholesale real-time LMP (Base RTP)

$P_{\text{clear}} = P_{\text{base}}$

- Varies every $T_S = 5\text{min}$

- $Q_{\text{min}}$ to $Q_{\text{max}}$

- $Q_{\text{clear}}$
RTP Double Auction Market – Congested

Unresponsive Loads

Responsive Loads

Demand Curve: sorted (P, Q) bids from transactive customers

Market clears at intersection of supply & demand curves

Rated Feeder Capacity

When constrained:
- Quantity \(Q_{\text{clear}}\) is constant at rated feeder capacity
- Price \(P_{\text{clear}}\) varies to keep load at rated capacity

Retail RTP based on wholesale real-time LMP (Base RTP)

\(P_{\text{base}}\)

\(P_{\text{clear}}\)

\(Q_{\text{min}}\)

\(Q_{\text{clear}}\)

\(Q_{\text{max}}\)

Q, Load (MW)
What about the Congestion Surplus?

- **Congestion surplus** is extra revenue collected from customers during constrained conditions (i.e. $P_{\text{clear}} > P_{\text{base}}$).

- Each customer’s surplus returned as billing rebate to maintain revenue neutrality.

- A PTR-like* incentive is also offered during congestion, based on customer’s bid history.

* peak time rebate
Fully Engaging Demand: What We’ve Learned from the Olympic Peninsula Demonstration
Customers can be recruited, retained, and will respond to dynamic pricing schemes if they are offered:

- Opportunity for significant savings (~10% was suggested)
- A “no-lose” proposition compared to a fixed rate
- Control over how much they choose to respond, with which end uses, and a 24-hour override
  - prevents fatigue: reduced participation if called upon too often
- Technology that automates their desired level of response
- A simple, intuitive, semantic interface to automate their response

Translates to control parameters:

\[ K, T_{max}, T_{min} \] (see Virtual Thermostat)
Significant demand response was obtained:

- 15% reduction of peak load
- Up to 50% reduction in total load for several days in a row during shoulder periods
- Response to wholesale prices + transmission congestion + distribution congestion
- Able to cap net demand at an arbitrary level to manage local distribution constraint
- Short-term response capability could provide regulation, other ancillary services adds significant value at very low impact and low cost)
- Same signals integrated commercial & institutional loads, distributed resources (backup generators)
Market-based Coordination of Thermostatically Controlled Loads With User Preferences
Coordination strategies falls into two categories:

   - Can achieve accurate aggregated response.
   - Needs aggregated modeling or estimation framework
   - Limitations: missing user preferences and customer privacy
2 Market-based coordination, several ways to model user response:

- Modify the wholesale price (Allocott, 2009), (Wolak, 2007):
  - Time of use, critical peak price
  - Model not accurate enough to obtain desired response
- Directly derive user response if user preferences are known (Pacshalidis, Li and Caramanis, 2012), (Bilgin, Caramanis and Pacshalidis, 2013).
- Collect information from users if user preferences are unknown (Chen, Li, Low and Doyle, 2010), (Li, Chen and Low, 2011)
  - Two key elements: **bidding** and **clearing**
Motivating Example

The GridWise demonstration project: (Fuller, Schneider and Chassin, 2011)

- The coordinator purchases energy from the wholesale market and sells it to users.
- Needs to respect the feeder capacity constraint.
- Two key elements: **bidding** and **clearing**.
Motivating Example

Fig. 1. user bid

Fig. 2. market clear

$P^*$: the marginal price for the coordinator to purchase energy from the wholesale market.
Motivating Example

- The demonstration project:
  - Novelties: a pre-fixed way to enable user-coordinator interaction.
  - Limitation: the aggregated user response curve is not accurate.

- Our objective
  - Formally formulate the problem.
  - bidding and clearing.
The Formulation

Market mechanism design:

- Need to find a mechanism $\Gamma = (M_1, \ldots, M_N, g(\cdot))$

- To setup a mechanism design problem:
  - Model the individual decision making
  - Define the group objective (social choice function)
The Formulation

Individual decision making:

- \( h_i(P_c; \theta_i) = \arg \max_{a_i} V_i(a_i; \theta_i) - P_c a_i \)

Subject to:

\[ 0 \leq a_i \leq E_i^m \]
Load dynamics

• The dynamics of residential loads can be captured by the Equivalent Thermal Parameter (ETP) model:

\[ x_i(k + 1) = A_i x_i(k) + B_{on}/B_{off} \]

• \( x_i(k) \) is the 2D system state, including the room temperature and mass temperature.
• The power state is regulated by a hysteretic controller.
• Each control setpoint corresponds to an energy consumption.
The Formulation

Group objectives:

\[
\max_{a_1, \ldots, a_N} \sum V_i(a_i; x_i(k), \theta_i) - C(\sum a_i)
\]

Subject to:

\[
\begin{cases}
0 \leq a_i \leq E_i^m \\
\sum a_i \leq D
\end{cases}
\]

Individual decision making:

\[
\max_{a_i} V_i(a_i; x_i(k), \theta_i) - P_c a_i
\]

Subject to:

\[
0 \leq a_i \leq E_i^m
\]

Assumptions:

- \(V_i\) is concave in \(a_i\) and continuously differentiable with respect to \(a_i\).
- Assume \(h_i(\cdot)\) is continuous, \(C(\cdot)\) is continuously differentiable.
- Every user is a price taker: no single load is large enough to dominate the market price.
The Proposed Mechanism*

Bidding strategy:

- Bid needs to help the coordinator to construct user response model
- The individual user response function \( h_i(\cdot) \):

Fig. 3. user response function

- We propose to use the illustrated step function to approximate the user response.

The Proposed Mechanism

Market clearing with complete information:

- The following clearing strategy maximizes the social welfare subject to a total energy constraint:

\[
P_c = \max\{P^*, \bar{P}\}
\]

Subject to:

\[
\begin{align*}
P^* &= C'\left(\sum h_i(P^*)\right) \\
\sum h_i(\bar{P}) &= D
\end{align*}
\]

Fig. 4. aggregated demand curve
Simulation Results

Fig. 5. market clearing with no congestion

Fig. 6. market clearing with congestion

Fig. 7. power trajectory on a mild day

Fig. 8. power trajectory on a hot day
Comments and questions?

Thank you!